Forest Floor, Soil, and Vegetation Responses to Sludge Fertilization in Red and White Pine Plantations[1]

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ABSTRACT

An undigested, nutrient-enriched papermill sludge applied to a 40-year-old red pine (*Pinus resinosa* Ait.) plantation at rates of 4, 8, 16, and 32 Mg/ha resulted in nitrogen application rates of 282, 565, 1130, and 2260 kg/ha. An anaerobically digested municipal sludge applied to a 36-year-old red pine and white pine (*Pinus strobus* L.) plantation at rates of 4.8, 9.7, and 19.3 Mg/ha resulted in nitrogen applications of 287, 578, and 1160 kg/ha. Both sludges produced significant forest floor increases in total salt, pH, and concentrations of nitrogen and phosphorus. The municipal sludge application also resulted in increased levels of trace elements and heavy metals. Accelerated humification developed along the interface between the sludge layer and the accumulated forest litter. Movement of nutrients from the forest floor into the soil was generally limited to nitrate, ammonia, and total phosphorus leaching into the upper soil layers. Very small fluctuations in nutrient levels occurred in the soil below 15 cm. Understory nitrogen and phosphorus levels increased in treated plots on both sites while cadmium increased on plots treated with municipal sludge. Understory biomass increases of up to 132% over controls were measured on sludge-treated plots. No metal toxicity symptoms were observed and sludge-treated understory vegetation remained green later into the growing season well after that on untreated plots had begun to discolor and approach dormancy. Overstory foliar nitrogen concentrations increased on sludge-treated plots, improving the N:P ratio in the pines. Increases in fasicle dry weight and needle length were noted in sludge-treated red pine, as were increases in radial growth in white pine. Evidence two growing seasons following sludge fertilization indicated an increased canopy weight, thus an enhanced potential for photosynthesis.

***Additional Index Words:* *Pinus resinosa* Ait., *Pinus strobus* L., forest fertilization, soil fertility, foliar nutrition, site productivity, heavy metals.**

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COMPLIANCE WITH SECONDARY wastewater treatment standards for discharge into surface waters, pursuant to the Federal Water Pollution Control Act Amendments of 1972, has confronted many municipalities and industries in the United States with a sludge disposal problem of increased proportion. Although questions have been raised concerning the presence of potentially deleterious constituents in wastewater sludges, land application of these treatment system residuals has received increased attention as a major cost-effective alternative for disposal (Forster et al., 1977). The impact of sludge application upon agricultural soils has been intensively investigated (Chaney et al., 1977; Lindsay, 1973; Kardos et al., 1977; Street et al., 1977) while forest soils have received less attention (Smith and Evans, 1977). As wastewater sludges are, with increasing frequency, being applied to forest soils, the impact of their constituents upon fertility and productivity is becoming a growing concern.

Productivity of forest sites has been shown in numerous studies to be responsive to addition of chemical fertilizer (White and Leaf, 1956; Bengtson et al., 1968; Pritchett, 1977). Significant percentages of N and P fertilizer materials were retained in forest soils in Florida (Fisher and Garbett, 1980), Ontario (Morrison et al., 1976), Washington (Heilman and Ekuan, 1980), and Alaska (Van Cleve and Moore, 1978) resulting in a general rise in soil fertility and site productivity. Other studies have found improved tree foliar nutrient status (Hippeli, 1976; Timmer and Stone, 1978; Donov et al., 1977; Wittwer et al., 1975) and increased tree growth (Tolle, 1976; Timmer et al., 1977; Rawson, 1972; Leaf et al., 1975) in stands fertilized with N, P, K, and lime. It is reasonable to anticipate that sludge-borne nutrients would increase soil fertility and upgrade site productivity by increasing the nutrient pool and the rate of nutrient cycling, as do chemical fertilizer additions. This is particularly true for the millions of hectares of nutritionally impoverished sandy outwash soils of northern Michigan, which are poorly suited to farming but useful in the production of forests (Harris, 1979).

While sludges are good sources of N, P, organic matter, and micronutrients (Sommers, 1977), they may also contain heavy metals (C, N, C, and Pb), which, if allowed to accumulate on site, could reduce vegetation production and pose a hazard in the food chain to animal and possibly to human consumers of game and wildland foods. Cadmium levels exceeding 0.1 mg/kg in soil have been shown to reduce agricultural crop yields by causing damage to root tissue (Turner, 1973). Cadmium levels below 1 mg/kg in items consumed by man and animals are known to be cumulatively toxic (Baker et al., 1977); however, soluble Cd represents a greater health risk than that of organic Cd in plant tissue (Allaway, 1977). The presence of heavy metals is likely to be far less troublesome in forest lands where products are generally of a nonedible nature (Smith and Evans, 1977). Silvicultural crops, unlike agricultural crops, offer longer rotations and can assimilate, redistribute, and immobilize a tremendous quantity of applied nutrients for long intervals.

Two field trials of wastewater sludge fertilization were conducted in pine plantations growing on sandy soils typical of northwestern Michigan. One sludge was from a papermill and characterized by low concentrations of heavy metals. The other sludge was from a medium-sized city and contaminated with moderate to high levels of heavy metals which could be traced to the presence of metal plating factories in that muncipality. Forest floor, mineral soil layers to the 1.2-m depth, and vegetation

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were examined to (i) document the redistribution of nutrients among these ecosystem components, (ii) assess the in-soil mobility and vegetation uptake of potentially hazardous heavy metals, and (iii) quantify the growth and nutritional impacts of sludge fertilization upon overstory and understory vegetation.

MATERIALS AND METHODS

Study Sites

Wastewater sludge fertilization trials were conducted on the Udell and Pine River Experimental Units of the Manistee National Forest in the northwest portion of Michigan's Lower Peninsula.

The Udell Experimental Forest, in Manistee County, is predominantly sandy moraines and medium altitude outwash plains of stratified, coarse unconsolidated deposits. Sludge fertilization trials were conducted in a 40-year-old red pine (*Pinus resinosa* Ait.) plantation growing upon soils of the Rubicon and Croswell series (Entic Haplorthods) which were derived from glacial outwash. These soils are well to moderately well drained, have low native fertility, and are unsuited for agriculture. The plantation, averaging 13 m (42.8 ft) in height, was thinned from an average basal area of 42.2 m^2/ha (184 ft^2/A) to 22 m^2/ha (96 ft^2/A) by removing two adjacent tree rows of every four in May 1976 prior to sludge application in June. Using height growth curves developed by Alban (1976), the site index was estimated to be 52 for red pine, a medium quality site (Buckman, 1962). The understory flora consisted primarily of *Pteridium, Comptonia, Vaccinium, Carex*, a variety of grasses, mosses, lichen, and numerous seedlings and suppressed saplings of *Quercus, Prunus*, and *Acer*.

The Pine River Experimental Forest, in Wexford County, is comprised of sandy moraines, outwash plains, and old lacustrine plains. Sludge fertilization trials were also conducted in 36-year-old plantations of red pine and white pine (*Pinus strobus* L.) growing upon soils which were an intergrade of Grayling series (Spodic Udipsamment) and the Menominee series (Alfic Haplorthod). Grayling sand is well drained, very rapidly permeable, droughty, low in native fertility, and unsuited for agriculture. Menominee sand is well to moderately well drained, of rapid to moderate permeability, of moderate available water capacity, and low to medium in native fertility marginally suiting it to agriculture. The plantations had mean heights of 12.0 m (39.6 ft) for red pine and 11.3 m (37 ft) for white pine and were thinned from an average basal area of 23.1 m^2/ha (100 ft^2/A) to 16.9 m^2/ha (73.8 ft^2/A) for red pine and 18.3 m^2/ha (80 ft^2/ha) for white pine in June 1976 prior to sludge application in July. Site index was estimated as 55 for red pine (Alban 1976), medium to high quality (Buckman, 1962), and 54 for white pine. Under red pine a somewhat sparse understory of *Pteridium, Comptonia, Vaccinium, Carex*, several grasses, mosses, lichen, and hardwood seedlings was present. Under white pine was found a more vigorous understory dominated by *Populus, Quercus, Prunus, Acer, Fraxinus*, and *Sassafras* seedlings, *Vaccinium, Comptonia, Pteridium, Rubus, Carex*, lilies and grasses.

Sludge Application

Sludge treatments on each site consisted of a single application of liquid, containing 5.5% total solids, sprayed over the forest floor. In the 40-year-old red pine plantation on the Udell Experimental Forest, sludge treatments equivalent to 0.0, 4.0 8.0, 16.0, and 32.0 dry Mg/ha were applied to randomized plots (81.4 by 20.4 m) with three replications. An undigested papermill sludge, enriched with ammonia and phosphoric acid, from the wastewater treatment facility at the Packaging Corporation of America in Filer City, Mich., was sprayed in June 1976 over the surface of slash and litter using an all-terrain liquid sludge spreading truck. In the 36-year-old red pine and white pine plantations on the Pine River Experimental Forest, sludge treatments equivalent to 0.0, 4.8, 9.7, and 19.3 dry Mg/ha were surface applied in July 1976 to plots (36.6 m in diameter) in a randomized, complete block design with three replications under each tree species. Study plots received municipal sludge which had been anaerobically digested for an average of 90 d at the Wastewater Treatment Plant in Cadillac, Mich. A portable pipeline and fire hose were used to distribute the sludge.

Sample Collection

Sludge samples were obtained directly from the nozzles of the all-terrain liquid sludge spreading truck and the fire hose during application. Samples were preserved with concentrated sulfuric acid (2 mL of H_2SO_4/L of liquid sludge) and stored in polyethylene bottles at 4°C.

In August of 1976 and 1977 (1 and 13 months after application), soils on both sites were sampled to determine changes in soil chemistry and surface soil physical properties. A bulk density soil sampler was used to obtain undisturbed cores at the 0- to 5- and 5- to 10-cm soil depths at 10 sampling points in each plot on the Udell site and in each white pine plot on the Pine River site and at five sampling points in each red pine plot on the Pine River site. A bucket auger was used to sample deeper soil layers: 15 to 30 cm, 45 to 60 cm, and 105 to 120 cm at four sample points per plot on the Udell site and two sample points per plot on the Pine River site.

During late August 1976 and 1977 (2 and 14 months after application), subsequent to bud set and needle maturation, branch samples were collected from the uppermost sunlit crown of the codominant trees, 5 trees per red pine plot and 10 trees per white pine plot, and placed into a composite plot sample paper bag. From these, shoot, fasicle, and needle samples from the current year's production were obtained. Needle length was recorded for 15 fasicles per plot. Diameter (DBH) measurements were then recorded using a diameter tape on 5 sample trees per red pine plot and 10 sample trees per white pine plot and increment cores were taken at breast height (1.4 m) on each of the same sample trees and the recent radial growth assessed for each stand. In April 1978 (22 months after application), during the dormant season, four codominant trees per Udell plot and two codominant trees per Pine River plot (20 trees/ha) were randomly selected, felled, and their overall length and mainstem internodal growth recorded for individual growing seasons from 1973 to 1977. A cross-sectional disk at the base of each tree's live crown was then removed and the upper stem radial growth measured for the previous four growing seasons.

In early September of 1976 and 1977 (2 and 14 months after application), understory vegetation and the forest floor (O horizons) were sampled on both sites. Eight locations per 0.17-ha plot on the Udell site and four locations per 0.10-ha plot on the Pine River Site were systematically selected for sampling. At each sampling location, all understory plants within a squaremeter area were cut at the groundline and placed in paper bags. The forest floor (a mor humus varying from 1 to 7 cm in thickness and dominated by a litter layer of pine needles, deciduous plant leaves, pine cones, fallen tree branches generally < 7 mm in diameter, in various stages of decomposition, lying upon a clearly defined mineral soil surface, including sludge applied on treated plots) was then collected within a 0.25-m^2 sample area and stored in paper bags.

Analytical Techniques

Sludge samples were analyzed by SERCO Laboratories of Roseville, Minn. Nitrate was determined using automated Cd reduction, and ammonia was measured with the Orion Ion-electrode (Milham et al., 1970). Total Kjeldahl nitrogen (TKN) was analyzed using the phenolate method (APHA 1971), and total P was determined by automated digestion with stannous chloride (U.S. EPA, 1974). Following wet digestion, total Cd, Ca, Cr, Cu, Fe, Pb, Mg, Mn, Ni, K, and Zn were determined by atomic absorption spectrophotometry (APHA, 1971). Boron was measured using plasma emission spectrophotometry (Dahlquist and Knoll, 1978) and total solids' content was determined gravimetrically.

Soil samples from the 0- to 5- and 5- to 10-cm soil layers were dried at 105°C for 24 h and soil moisture content and bulk density determined. Soil samples from each plot were composited for each of the five soil layers examined. All soil was passed through a 2-mm screen prior to chemical analysis. Soil chemical analysis was conducted by the Research Analytical Laboratory at the University of Minnesota at St. Paul and by the U.S. Forest Service Research Laboratory at East Lansing, Mich. Nitrate plus nitrite and ammonia were extracted with 1N KCl (Black et al., 1965) and analyzed using a Technicon Autoanalyzer II (Technicon 1971). Total Kjeldahl nitrogen was measured using the macro-Kjeldahl method (Black et al., 1965). total P was determined by nitric–perchloric acid digestion (Tandon et al., 1968) and plasma emission spectrophotometry (Dahlquist and Knoll, 1978). Extractable K, Ca, Mg, and Na were extracted with $1N$ NH_4Ac and analyzed by atomic absorption spectrophotometry (Dahlquist and Knoll, 1978). Iron, copper, zinc, manganese, cadmium, lead, chromium, and nickel were extracted using DPTA and TEA (Lindsay and Norwell, 1978) and analyzed by plasma emission spectrophotometry. Boron was determined using hot water extraction and emission spectrophotometric analysis (Dahlquist and Knoll, 1978). Cation exchange capacity (CEC) was measured by summation (Black et al., 1965) and exchangeable acidity was accomplished with a $0.2N$ TEA plus $0.5N$ $BaCl_2$ extraction and titration with $0.1N$ HCl. Electrical conductivity and pH were measured on a saturated paste of one part soil to one part deionized distilled water using, respectively, a conductivity meter and a glass electrode. Percentage of organic matter was determined by the loss on ignition method.

All forest floor, understory, and overstory vegetation samples were dried in a forced draft oven at 75°C for 24 h, weighed, and ground in a Wiley mill with a 20-mesh screen. Samples were combined by component into one composite sample per plot and chemically analyzed at the Research Analytical Laboratory of the University of Minnesota at St. Paul. Total nitrogen was determined by the semi-micro Kjeldahl method (Black et al., 1965). Following dry ashing at 485°C, tissue samples were dissolved in $2N$ HCl and P, K, Ca, Mg, Al, Na, Fe, Mn, Zn, Cu, B, Co, Pb, Cr, Cd, and Ni were measured using inductively coupled plasma emission spectrophotometry (Dahlquist and Knoll, 1978). Forest floor pH and electrical conductivity were measured on a mixture of four parts tissue to one part deionized distilled water using, respectively, a glass electrode and conductivity meter at the U.S. Forest Service Research Laboratory in East Lansing.

RESULTS AND DISCUSSION

Sludge Composition

The major difference in quality between the two sludges was the presence of high levels of trace elements and heavy metals in the digested municipal sludge (Table 1). Zinc, copper, lead, nickel, and cadmium levels of 1650, 1040, 960, 192, and 440 mg/kg in the municipal sludge approximated or exceeded the respective median values of 1740, 850, 500, 82, and 16 mg/kg reported by Sommers (1977) for typical municipal sludges produced in the United States. The unusually high Cd level in this sludge was the result of a high Cd discharge from an electroplating industry into the municipal wastewater treatment system. Zinc, copper, lead, nickel, and cadmium concentrations in the raw papermill sludge were much lower than the median values, being 542, 48, 49, 17, and 5 mg/kg, respectively.

Total N and total P were, respectively, 6.0 and 7.8% in the municipal sludge and 7.0 and 1.0% in the papermill sludge (Table 1). Typical municipal sludge values for N and P average 3.3 and 2.3%, respectively (Sommers, 1977). Both sludges contained 5.5% total solids. Carbon to nitrogen ratios were 13:1 for the municipal sludge and 9:1 for the papermill sludge. These values approximated the 12:1 ratio considered optimum for humus mineralization (Pritchett, 1979). Zinc to cadmium ratios were 4:1 for the municipal sludge and 108:1 for the papermill sludge. Zinc to cadmium ratios exceeding 100:1 are acceptable in materials used as soil amendments, as sludges containing low Zn with respect to Cd may produce an unwanted Cd buildup in soil and vegetation (Allaway 1977).

Nitrogen application rates with papermill sludge were 282, 565, 1130, and 2260 kg/ha (Table 1). Phosphorus

Table 1—Elemental composition and application rates for municipal and papermill wastewater sludges, 1976.

	Udell site					Pine River site			
	Papermill (undigested) sludge					Municipal (digested) sludge			
Sludge application rate, Mg/ha		4.0	8.0	16.0	32.0		4.8	9.7	19.3
Element	Concentration	Application rate				Concentration	Application rate		
	mg/kg	kg/ha				mg/kg	kg/ha		
NH_4-N	4 450	17.8	35.5	71.0	142	16 600	79.5	160.0	320
NO_3-N	1 150	4.4	9.2	17.6	35.2	24	0.1	0.2	0.4
N	70 600	282	565	1 130	2 260	60 000	287	578	1 160
P	10 000	40.0	80.0	160	320	78 200	374	753	1 510
K	2 100	8.4	16.8	33.6	67.2	1 540	7.4	14.8	29.7
Ca	17 400	75.2	150	301	602	14 000	67.0	135	270
Mg	4 900	21.2	42.4	84.8	170	7 760	37.1	74.7	150
Fe	2 400	10.4	20.8	41.6	83.2	1 420	6.8	13.7	27.3
Mn	1 060	4.6	9.2	18.4	36.8	1 540	7.4	14.8	29.7
Zn	542	2.4	4.8	9.6	19.2	1 650	7.8	15.9	31.7
Cu	48	0.2	0.4	0.8	1.6	1 040	5.0	10.0	20.0
B	43	0.2	0.4	0.7	1.4	2	0.01	0.02	0.03
Pb	49	0.2	0.4	0.9	1.8	960	4.6	9.3	18.5
Cr	27	0.1	0.2	0.5	1.0	780	3.6	7.5	15.0
Cd	5	0.02	0.04	0.1	0.2	440	2.1	4.3	8.5
Ni	17	0.1	0.2	0.3	0.6	192	0.9	1.9	3.7

application rates were 40, 80, 160, and 320 kg/ha. Other nutrient and heavy metal loadings were low, even at the highest rate of sludge application.

Nitrogen application rates with municipal sludge were 287, 578, and 1160 kg/ha. Most of the N applied in both sludges was present as organic N. The percentage of total N present as ammonia varied from 6% (up to 142 kg/ha) in the papermill sludge to 28% (up to 320 kg/ha) in the municipal sludge. Nitrate additions were minor with both sludges, < 2% of total N (up to 35.2 kg/ha).

Total P additions with municipal sludge were 374, 753, and 1510 kg/ha, amounting to P loading rates an order of magnitude greater than those supplied by the papermill sludge at equivalent sludge application rates. Copper, lead, chromium, nickel, and cadmium in the municipal sludge were applied in amounts one to two orders of magnitude greater than with the papermill sludge.

Forest Floor

Fourteen months following sludge application, N and P concentrations in the forest floor were significantly increased on both study sites (Table 2). Nitrogen values of < 1% were increased to nearly 2% by the 32 Mg/ha papermill sludge application and to > 1.3% by the 19.3 Mg/ha municipal sludge application. Phosphorus levels approximating 0.05% were increased to 0.37% by the 32 Mg/ha papermill sludge application and to as high as 1.45% by the 19.3 Mg/ha municipal sludge application.

Application of papermill sludge on the Udell site did not produce increased trace element and heavy metal concentrations in the forest floor. Application of municipal sludge on the Pine River site did produce significant increases in the levels of trace elements and heavy metals (Table 3). Zinc levels as low as 58 mg/kg in the control were increased by the heaviest sludge rate to > 1000 mg/kg in the forest floor under both red pine and white pine. Cadmium concentrations near 1 mg/kg were elevated by the highest sludge application rate to > 100 mg/kg. This hundred-fold increase in the post-treatment Cd levels of the forest floor on the Pine River site raised questions concerning Cd accumulation in soil and vegetation and transmission to wildlife and possibly humans via the food chain. Copper, lead, chromium, and nickel also showed significant forest floor increases following municipal sludge application. However, because these elements are ionically less mobile than Cd or Zn and are largely immobilized in soil humus or the upper soil layers by being either strongly adsorped by soil colloids or precipitated by soil anions, they are believed less hazardous in the ecosystem.

Forest floor pH increased in direct relation to the amounts of sludge applied on both study sites. Basic cation additions elevated pH in the red pine forest floor to as high as 6.1 in 1976 while control pH levels averaged 4.2. Although cation leaching, nutrient assimilation by plants and nitrification resulted in a pH decrease at all treatment levels 14 months after sludge application, the pH of sludge-treated plots remained significantly greater than controls.

Electrical conductivity trends were similar to those discussed for pH. Control electrical conductivity values near 0.3 dS/m were increased to > 2.2 dS/m on treated plots. While sludge applications significantly increased the total salts content of the forest floor upon both study sites, the electrical conductivity was well below the 4 dS/m threshold typical of saline soils. Although normal leaching will eventually remove these added salts from the forest floor, it is important to recognize that long-term maintenance of high salt levels on a site with finer-textured soil could adversely affect soil structure and productivity.

The most obvious physical change in the forest floor following sludge fertilization was an increase in dry weight resulting from the solids applied to each treated plot. Dry weight increased 142%, from 2062 g/m^2 to 4982 g/m^2, on Udell Forest plots treated with 32 Mg of papermill sludge/ha. Dry weights on the Pine River site under red pine increased 73%, from 1898 g/m^2 to 3292 g/m^2, and under white pine increased 72%, from 2079 g/m^2 to 3551 g/m^2, on plots treated with 19.3 Mg of municipal sludge/ha. Although the N supplied with treatment narrowed the carbon to nitrogen ratio, the variation in forest floor weight under each stand was a function of the applied solids. Linear regression r^2 values correlating sludge application rate with forest floor dry weight ranged from 0.83 to 0.99.

Table 2—Forest floor N and P 14 months after sludge application.

	Udell site					Pine River site			
	Papermill					Municipal			
Sludge application rate, Mg/ha	0.0	4.0	8.0	16.0	32.0	0.0	4.8	9.7	19.3
	%								
TKN									
Red pine	0.93a*	1.32b	1.52b	1.78c	1.96c	0.70a	0.98b	1.21bc	1.34c
White pine	–	–	–	–	–	0.76a	1.10ab	1.33b	1.32b
Total P									
Red pine	0.07a	0.16a	0.21a	0.34b	0.37b	0.05a	0.54b	1.15c	1.25c
White pine	–	–	–	–	–	0.05a	0.59b	1.12c	1.45c

* Means, within the same study site and species, followed by different letters are significantly different at the 0.05 level (L.S.D.).

Table 3—Forest floor trace elements and heavy metals 14 months after sludge application.

	Pine River site			
Municipal sludge application rate, Mg/ha	0.0	4.8	9.7	19.3
	mg/kg			
Zn				
Red pine	58a*	527b	1 060c	1 150c
White pine	79a	558b	1 050c	1 330c
Cd				
Red pine	0.8a	51.9a	110.0b	117.0b
White pine	1.1a	53.2b	108.0c	136.0c
Cu				
Red pine	4a	97b	210b	230b
White pine	4a	105b	217c	286c
Pb				
Red pine	68a	165a	283b	297b
White pine	70a	194b	293c	344c
Cr				
Red pine	2a	78a	173b	190b
White pine	3a	92b	179c	234c
Ni				
Red pine	3a	17b	33c	37c
White pine	3a	19b	35c	45c

* Means, within the same species, followed by different letters are significantly different at the 0.05 level (L.S.D.).

In 1977 new fermentation zones along the margin of the sludge layer were observed in the forest floor. This change in structure was best developed on the high sludge dosage plots indicating locally favorable C:N ratios at the sludge–litter interface.

It should be noted that 14 months following application, the sludge and the forest floor were as yet largely separate entities comingled upon the soil. Although the applied sludge largely determined the mass of the forest floor and had begun to significantly influence the chemical properties of the forest floor, it must be recognized as a distinctly exogenous source of organic matter and nutrients, not having been produced and deposited onsite as has the forest floor. As evidenced by the newly observed zones of fermentation at the sludge–litter interface, eventual incorporation of sludge-borne nutrients and organic matter into the soil, vegetation, and forest floor appears likely.

Soil

A significant increase in NO_3-N as late as 13 months subsequent to sludge application on plots receiving the highest dosage rates was the greatest effect of treatment on the 0- to 5-cm soil layer (Table 4). Ammonia levels were significantly elevated by papermill sludge treatments on the Udell site. Nitrogen application with treatment did not increase soil TKN levels implying that a majority of the N, applied as organic N, remained in the forest floor. Significant increases in NO_3-N and NH_4-N in the upper soil layer resulted from leaching of these soluble N forms as sludge decomposition ensued following treatment. During snowmelt and other recharge periods, subsequent to sludge fertilization, substantial movement of NO_3-N into groundwater below the rooting zone has been reported in forests of this region (Brockway and Urie, 1983).

Total P increased from 85 mg/kg on control plots to 141 mg/kg with the 32 Mg/ha papermill sludge treatment. Soluble P in the liquid fraction of this phosphoric acid-enriched sludge elevated total P in the treated plots by movement of soluble P into the surface soil during and shortly after sludge application. Although P on the Pine River site also increased following municipal sludge treatment, higher native P levels and greater site variability diminished the impact of the supplemental P upon the soil.

Table 4—Soil N and P, 0- to 5-cm depth, 13 months after sludge application.

	Udell site					Pine River site			
	Papermill					Municipal			
Sludge application rate, Mg/ha	0.0	4.0	8.0	16.0	32.0	0.0	4.8	9.7	19.3
	mg/kg								
NO_3-N									
Red pine	0.1a*	1.3ab	1.5ab	4.6b	19.6c	0.1a	0.4a	0.3a	1.5b
White pine	–	–	–	–	–	0.7a	1.1a	2.4ab	9.1b
NH_4-N									
Red pine	7.5a	13.1a	15.3ab	19.7ab	29.6b	14.1a	21.4a	10.8a	19.0a
White pine	–	–	–	–	–	17.8a	19.5a	19.0a	20.6a
TKN									
Red pine	627a	690a	603a	703a	683a	613a	667a	623a	623a
White pine	–	–	–	–	–	633a	657a	567a	637a
Total P									
Red pine	86a	97a	99a	102a	141b	109a	111a	137a	146a
White pine	–	–	–	–	–	93a	132ab	109ab	150b

* Means, within the same study site and species, followed by different letters are significantly different at the 0.05 level (L.S.D.).

Micronutrient and heavy metal concentration increases in the surface soil layer on both study sites were variable and poorly related to sludge treatment levels. Zinc, copper, chromium, lead, and nickel levels did not increase with sludge application, and cadmium concentrations increased only under white pine treated with municipal sludge. Although the heavy metal laden municipal sludge could be normally anticipated to produce elevated contaminant levels in mineral soil, in this instance, initial retention of these in the forest floor was responsible for the diminished differential effect of the two different sludges upon soil heavy metal concentrations (Brockway, 1979). Surface soil Cd levels ranged from 0.1 to 0.4 mg/kg in control and treated plots on both study sites, generally exceeding the 0.1 mg/kg Cd level described by Turner (1973) as causing root damage in growing vegetable crops.

Cation additions had minimal impact upon total base reserves in the surface soil layer. Increases in CEC and base saturation were variable and poorly related to sludge treatment rates. Soil electrical conductivity initially increased as sludge supernatant and soluble salts leached from the treated forest floor entered the 0- to 5-cm soil layer. This effect diminished as soluble nutrient forms were assimilated or leached from the soil profile. The movement of nutrients from the forest floor into the soil produced little change in soil pH and carbon to nitrogen ratio. Although soluble N entered the 0- to 5-cm soil layer, not enough was retained there to significantly narrow the carbon to nitrogen ratio.

In soil layers below the 5-cm depth fluctuations in soil nutrient concentrations were far less pronounced. Nitrate was increased on both study sites in plots receiving the highest rates of sludge treatment. While NO_3-N levels generally remained < 2 mg/kg, levels as high as 10.2 mg/kg were detected in the 5- to 10 cm soil layer on plots receiving 32 Mg of papermill sludge/ha. Ammonium concentrations were also somewhat elevated in soils under the highest sludge treatment rates. Maximum NH_4-N levels of 18.1 mg/kg were measured in the 5- to 10-cm soil layer on plots receiving 19.3 Mg/ha of municipal sludge. Total Kjeldahl nitrogen did not increase in the deeper soil layers. Organic N appears to have been immobilized in the forest floor while mobile N forms, NO_3 and NH_4, leached downward into the mineral soil. As in the case of total N, the levels of most other elements did not seem to change below the 5-cm depth. The influence of the sludge treatements upon the chemistry of lower soil layers was minimal because (i) the most prominent N form, NO_3, leached rapidly through the coarse sand, (ii) the lower layers, having generally lower CEC values (0.2 to 5), were less able to adsorb supplemental nutrients, and (iii) 13 months after application a substantial portion of the applied nutrients remained in the as yet partially decomposed sludge layer in the forest floor.

Soil bulk density and moisture content in the upper 10 cm, measured once each growing season on both study sites, were unaffected by the sludge treatments.

Understory Vegetation

The nutrient status of understory vegetation on both study sites benefited significantly from N and P supplied with sludge application (Table 5). Background N levels near 1% were increased to concentrations exceeding 2% and approaching 3% with the highest rates applied. Concurrently, P concentrations near 0.1% were increased to levels of approximately 0.3%. These nutritional responses were observed for N and P on both study sites by the end of the initial growing season following treatment. Potassium, calcium, and magnesium did not show trends of uptake significantly related to sludge treatment. Control levels of N, P, and other macronutrients were comparable to those reported for similar species assemblages (Gerloff et al., 1964).

Significant increases in understory Cd concentrations were measured in 1976 and 1977 on plots treated with municipal sludge. Background understory Cd levels < 1 mg/kg were increased in 1976 to > 22 mg/kg in vegetation on plots treated at the 19.3 Mg/ha rate. In 1977, understory Cd concentrations on the same plots were only 2 to 3 mg/kg, indicating that the high Cd levels measured in 1976 were the result of surface contamination rather than assimilation alone. Understory production increases in 1977 may have also contributed to dilution of Cd concentrations (Table 5). As soil Cd levels generally did not increase with sludge treatment, Cd assimilated directly by fine roots present in the enriched forest floor accounted for the increased uptake during the 1977 growing season.

Cadmium has been shown to accumulate in foliage rather than in seeds and fruit. Understory Cd values reported here are for all combined above ground plant parts and are lower than concentrations in foliage alone to which browsing wildlife on summer range would be exposed. According to recommendations by Baker et al. (1977), foliar Cd levels should be maintained below 1 mg/kg to avoid potential problems with Cd buildup in the food chain. However, studies of 7 years' duration, where cattle and swine were fed forage grown on high-Cd sludge-fertilized soils or were allowed to live in direct contact with the sludge-treated environment, found no significant differences in fertility or disease between control and experimental herds even though kidneys and livers accumulated Cd in proportion to the duration and intensity of each animal's exposure to sludge (Fitzgerald, 1982). Though exposed to high-Cd concentrations in this study, understory vegetation apparently suffered little ill effect, as production increased and nutrition improved with sludge application. The conclusion drawn from these data and the literature is that although Cd can be definitely toxic to living organisms, in many environments the degree of hazard to the organisms present is poorly understood and the controversy surrounding this issue very much unresolved.

Cadmium levels in understory plants treated with the low metal papermill sludge remained in the nonhazardous range of 1 mg/kg or less. Other heavy metals (Cr, Pb, and Ni) and micronutrients (Fe, Mn, Zn, Cu, and B) exhibited uptake trends unrelated to sludge treatment. Metal toxicity symptoms were not apparent on either study site.

During 1976 (2 months after treatment), understory biomass production was significantly decreased by the 32 Mg/ha sludge application. This was the result of a smothering effect the high application rate had upon the developing flora. By 1977 (14 months after treatment), understory production increased on all plots, a result of overstory thinning during the previous year (McConnel and Smith, 1970). Understory biomass under red pine treated with papermill sludge increased 92% to a level of 54.6 g/m^2 in comparison to control levels of 28.5 g/m^2 while that under red pine treated with municipal sludge increased 132% to 50.4 g/m^2 in contrast to control levels of 21.7 g/m^2. Production in the understory beneath white pine treated with municipal sludge increased 26% to 45.4 g/m^2 above control levels of 35.9 g/m^2. Unlike red pine plots, overstory thinning on white pine plots resulted in a greater increase in understory biomass, from 14.9 to 35.9 g/m^2, than did sludge treatment.

Visual inspection of the plots receiving the highest sludge treatment rates revealed lush green growth of bracken fern during the late growing season when vegetation in the control plots had already begun to discolor and approach dormancy. This response was similar to that produced when luxury consumption of abundant N following mineral fertilization prolongs succulent growth.

Table 5—Understory nutrition and growth 2 and 14 months after sludge application.

	Udell site					Pine River site			
	Papermill					Municipal			
Sludge application rate, Mg/ha	0.0	4.0	8.0	16.0	32.0	0.0	4.8	9.7	19.3
	%								
TKN									
1976									
Red pine	1.03a*	1.27ab	1.63ab	2.34b	2.35b	1.15a	1.81ab	1.93ab	2.66b
White pine	–	–	–	–	–	1.41a	1.51a	2.12ab	2.41b
1977									
Red pine	1.26a	1.54ab	1.94bc	2.42c	2.28c	1.21a	1.74b	2.10b	2.96c
White pine	–	–	–	–	–	1.36a	1.71a	2.17b	2.81c
Total P									
1976									
Red pine	0.08a	0.09a	0.15a	0.19a	0.39b	0.12a	0.22b	0.28bc	0.33c
White pine	–	–	–	–	–	0.16a	0.26b	0.34b	0.34b
1977									
Red pine	0.11c	0.14ab	0.19abc	0.25c	0.22bc	0.13a	0.27b	0.27bc	0.37c
White pine	–	–	–	–	–	0.17a	0.24b	0.29b	0.36c
	mg/kg								
Cd									
1976									
Red pine	0.4a	0.5ab	0.5ab	0.7b	1.0c	0.7a	10.7ab	16.4b	13.8b
White pine	–	–	–	–	–	0.9a	16.3ab	22.7b	22.1b
1977									
Red pine	0.2a	0.3ab	0.4abc	0.5bc	0.6c	0.3a	2.6b	1.4ab	2.0b
White pine	–	–	–	–	–	0.6a	1.1ab	1.0a	2.8b
	g/m^2								
Biomass									
1976									
Red pine	24.8ab	27.4a	17.2ab	11.4ab	11.0b	21.5a	6.3a	12.8a	16.9a
White pine	–	–	–	–	–	14.9a	16.9a	11.3a	9.7a
1977									
Red pine	28.5a	40.9ab	40.0bc	28.6a	54.6c	21.7a	22.4a	46.8ab	50.4b
White pine	–	–	–	–	–	35.9a	41.6a	46.6a	45.4a

* Means, within the same study site and species, followed by different letters are significantly different at the 0.05 level (L.S.D.).

Overstory Trees

Foliar N concentrations increased significantly in pines growing on plots receiving the 16 Mg/ha or greater sludge

Table 6—Overstory nutrition 2 and 14 months after sludge application.

	Udell site					Pine River site			
	Papermill					Municipal			
Sludge application rate, Mg/ha	0.0	4.0	8.0	16.0	32.0	0.0	4.8	9.7	19.3
N:P ratio									
1976									
Red pine	6.6	6.6	6.7	7.0	7.4	7.0	6.5	7.7	8.2
White pine	–	–	–	–	–	6.6	6.9	7.3	8.1
1977									
Red pine	7.3	7.3	8.1	9.2	11.0	6.3	6.9	7.6	10.3
White pine	–	–	–	–	–	7.1	7.7	8.0	10.2
	%								
TKN									
1976									
Red pine	1.09a*	1.09a	1.13a	1.17ab	1.24b	1.10a	1.14ab	1.17b	1.28c
White pine	–	–	–	–	–	1.09a	1.16ab	1.24b	1.36c
1977									
Red pine	1.25a	1.29a	1.39a	1.57b	2.03c	1.09a	1.17ab	1.36b	1.59c
White pine	–	–	–	–	–	1.30a	1.36ab	1.47b	1.68c
Total P									
1976									
Red pine	0.17a	0.16a	0.17a	0.17a	0.17a	0.16a	0.18b	0.15a	0.16a
White pine	–	–	–	–	–	0.16a	0.17a	0.17a	0.17a
1977									
Red pine	0.17a	0.18a	0.17a	0.17a	0.18a	0.17a	0.17a	0.18a	0.16a
White pine	–	–	–	–	–	0.18a	0.18ab	0.18a	0.17b

* Means, within the same study site and species, followed by different letters are significantly different at the 0.05 level (L.S.D.).

Table 7—Overstory growth before treatment and 2 and 14 months after sludge application.

	Udell site					Pine River site			
	Papermill					Municipal			
Sludge application rate, Mg/ha	0.0	4.0	8.0	16.0	32.0	0.0	4.8	9.7	19.3
	mg								
Fasicle dry weight									
1977									
Red pine	49a*	51a	67b	66b	72b	44a	50ab	54ab	66b
White pine	–	–	–	–	–	28ab	25a	29ab	32b
	mm								
Needle length									
1977									
Red pine	93.6a	96.4a	110.0b	114.0bc	122.0c	86.9a	93.6a	95.9a	110.0a
White pine	–	–	–	–	–	59.7a	65.0a	64.9a	67.5a
Radial growth at breast height									
1976									
Red pine	1.7a	1.7a	1.7a	1.9a	1.8a	2.0a	2.0a	2.4a	1.7a
White pine	–	–	–	–	–	1.8a	2.0ab	2.2ab	2.5b
1977									
Red pine	1.6a	1.5a	1.6a	1.6a	1.5a	1.8a	1.8a	2.0a	1.7a
White pine	–	–	–	–	–	1.5a	1.8ab	2.0ab	2.2b
Radial growth at base of live crown									
1974 + 1975									
Red pine	7.0a	6.5bc	7.1a	6.7abc	6.4c	6.7a	7.9a	6.5a	6.9a
White pine	–	–	–	–	–	8.2ab	9.0a	8.8ab	6.8b
1976 + 1977									
Red pine	6.5ab	6.4ab	6.9a	6.3ab	6.0b	6.2a	7.1a	4.7a	6.9a
White pine	–	–	–	–	–	6.9a	6.7a	5.8ab	4.9b

* Means, within the same study site and species, followed by different letters are significantly different at the 0.05 level (L.S.D.).

application rate (Table 6). In 1977 (14 months after treatment) foliar N levels in controls ranged from 1.09 to 1.30% while those in plots receiving the 32 Mg/ha papermill sludge treatment or the 19.3 Mg/ha municipal sludge treatment ranged from 1.36 to 2.03%. These TKN concentrations represent increases of 38% in red pine on the Udell site and 25 and 29%, respectively, for red pine and white pine growing on the Pine River site. Foliar P levels were not significantly altered by sludge nutrient applications on either site; therefore, increases in the N:P ratio occurring in trees receiving the highest sludge treatment rates were primarily the result of increased N uptake. The overstory trees on the control plots had foliar nitrogen to phosphorus ratios which fell into the lower end of the range tolerated by pines, 5:1 to 16:1 (van den Driessche, 1974). Addition of N in sludge-treated plots improved this ratio, allowing it to approach the optimum for pines of 10:1. Assimilation of other nutrients and heavy metals was generally unrelated to sludge treatments.

The initial overstory growth responses which could be related to sludge treatment appeared as increases in fasicle dry weight and needle length (Table 7). Fasicle dry weight was significantly increased on red pine plots treated with papermill sludge and municipal sludge; however, the weights for white pine fasicles treated with municipal sludge were not significantly greater than those in controls. Dry weight increases represented as much as a 47% increase over controls in red pine treated with papermill sludge and a 50% increase over controls in red pine treated with municipal sludge. Needle length for red pine treated with papermill sludge at the 32 Mg/ha rate exhibited a significant increase of 30% to 122 mm over control values of 93.6 mm. Needle length increases with increasing municipal sludge application rates were not statistically significant. Needles obtained from treated plots, upon visual inspection, appeared darker green in color than those from control plots.

Significant increases in radial growth at breast height of as much as 39% in 1976 and 47% in 1977 for white pine were related to municipal sludge treatment. Radial growth at breast height in red pine was unrelated to papermill or municipal sludge application. Increase in radial growth at the base of the live crown of either species did not develop with sludge treatment. All remaining tree growth parameters could not be related to sludge treatment.

These results were similar to those of Miller et al. (1976) and Tolle (1976) who found increases in foliar biomass, needle length, and stem radial growth in pines subject to nutrient additions, particularly N. Mader and Howarth (1970) have demonstrated that growth in red pine was significantly related to foliar nutrient levels and Miller and Cooper (1973) have determined that volume growth was maximized when foliar N exceeded 2%. The overall improvement in N nutrition with sludge treatment and trends of increased fasicle dry weight and needle length indicated a slow buildup in canopy weight and photosynthetic potential. Other growth parameters have generally not yet responded to treatment because, according to Leaf et al. (1970), a lapse time of 2 to 5 years from the date of fertilizer treatment is needed to remedy nutrient deficiencies and to build up an increased photosynthetic capacity thereby permitting the trees to demonstrate a growth response to nutrient additions in their environment. This lag time is of particular importance in trees which exhibit predeterminant growth patterns, as do pines. Subsequent growing seasons on these study plots should produce increasing growth responses to treatment among the overstory trees.

Distribution of Elements

Although available data was not sufficient to reconstruct a complete nutrient budget for each site, redistribution of elements among forest floor, understory, and loss to groundwater was computed. Of the applied N, retention in the forest floor averaged 37% among all application rates. Less than 1% of the applied N was assimilated by the understory vegetation and approximately 7% was lost to groundwater 22 months after treatment (Brockway, 1979). Where temporary water saturated conditions existed above finer-textured bands in the sandy soil, evidence of N loss through denitrification was detected (Brockway and Urie, 1983). Assuming our methods were sufficiently sensitive, the remaining portion of applied N must be accounted for by soil storage, overstory vegetation uptake, and loss to the atmosphere by direct volatilization of ammonia, dinitrogen and nitrous and nitric oxides shortly following sludge application. Of the applied P, retention in the forest floor averaged 46%. Less than 1% of the P applied was assimilated by understory plants and losses to groundwater were nil. As increases in P concentrations in overstory trees were not observed, soil storage must have largely accounted for the remaining applied P. Of the applied Cd, retention in the forest floor averaged 69%. Less than 1% of that applied was taken up by understory vegetation and losses to groundwater, based on suction lysimeter data, were nil (Brockway, 1979). As increases in Cd concentrations in overstory trees were not observed, soil storage must have accounted for the remaining applied Cd.

Elemental concentrations, while not alone an ideal tool for constructing site nutrient budgets, have proved useful here in providing a preliminary indication of the initial effect of wastewater sludge applications on the redistribution of nutrients among various components of the forest ecosystems examined. As appears evident 14 months following treatment, a major portion of the applied elements remained in the forest floor with the partially decomposed sludge. Soil storage of N, P, and Cd and overstory assimilation and atmospheric volatilization of N also appeared to be important.

Site Productivity

Miller (1981), in reviewing the major concepts of forest fertilization, stated that commercial fertilizer applications primarily benefit trees by enhancing foliage production prior to canopy closure or follow thinning. The resulting acceleration in growth has the effect of shortening rotation length. However, if large quantities of nutrients, as those applied with high-rate wastewater sludge applications, are delivered to a forest site, the effect upon overall site quality can be substantial. In this study, the highest sludge application rate of 32 Mg/ha (2260 kg N/ha) represents an amount of such magnitude, while the lower rates are closer to commercial scale applications. One may speculate that high-rate sludge applications, repeated at 5-year intervals, would lead to a substantial improvement in site productivity over the long term.

The application of wastewater sludges to forest sites has become a question of balancing benefits to plant growth against risks of ecosystem contamination with heavy metals or other potentially deleterious materials. While sludge application rates approximating 8 Mg/ha (565 kg N/ha) may have substantially less immediate effect on plant nutrition and growth than higher rates, other data indicate that unacceptable levels of NO_3-N leaching occur on pine sites treated with > 12 Mg/ha (850 kg N/ha) of undigested sludge and 19 Mg/ha (1140 kg N/ha) of digested sludge (Brockway and Urie, 1983), undigested sludge apparently decomposing at a more rapid rate. On-site retention of N is optimal with applications of sludge in spring, maximizing opportunities for plant uptake while minimizing those for NO_3-N loss by leaching. The presence of potentially toxic metals in sludge may also limit application rates or render a highly contaminated sludge unusable for forest application. While federal guidelines for sludge application of metals to the land have been tentatively established, the capacity of various forest ecosystems to tolerate heavy metal introductions and maintain their productive potential requires further quantification. A more thorough delineation of the responses of forest ecosystems to wastewater sludge additions would require observations of longer term, particularly if repeated sludge applications are contemplated.

CONCLUSION

The addition of wastewater sludges to pine plantations growing on nutrient-poor outwash soils has increased concentrations on N and P in upper soil layers and enhanced the short-term growth and nutrient status of understory (with N and P) and overstory (with N) vegetation, even when substantial quantities of heavy metal were also applied. Sludge application in early summer at rates approximating or exceeding 8 Mg/ha were adequate to stimulate these short-term responses; however, the 16, 19.3, and 32 Mg/ha rates may lead to excessive NO_3-N leaching and a resulting enrichment of groundwater. Because a large portion of nutrients and heavy metals remained in the forest floor with the partially decomposed sludge 14 months after application, longer-term studies will be required to determine the ultimate fate of these elements in the ecosystem. While the initial response to forest fertilization with wastewater sludges is encouraging, additional information is needed concerning each ecosystem's tolerance for heavy metal introductions and the effect which repeated sludge applications would have on long-term productivity and environmental quality.

REFERENCES

1. Alban, D.H. 1976. Estimating red pine site index in Northern Minnesota. USDA Forest Service, North Central Forest Exp. Stn. Res. Paper, NC-130.
2. Allaway, W.H. 1977. Food chain aspects of the use of organic residues. p. 283–298. *In* L.F. Elliott and F.J. Stevenson (ed.) Soils for management of organic wastes and waste waters. Am. Soc. of Agron., Madison, Wis.
3. American Public Health Association. 1971. Standard methods for the examination of water and wastewater. 39th Ed. APHA, New York.
4. Baker, D.E., M.C. Amacher, and W.T. Doty. 1977. Monitoring sewage sludges, soils and crops for zinc and cadmium. p. 261–281. *In* R.C. Loehr (ed.) Land as a waste management alternative. Ann Arbor Science Publishers, Ann Arbor, Mich.
5. Bengtson, G.W., R.H. Brendemuehl, W.L. Pritchett, and W.H. Smith (ed.) 1968. Forest fertilization theory and practice. Symp. on Forest Fertilization, Gainsville, Florida. April 1967. Tennessee Valley Authority, Muscle Shoals. Ala.

6. Black et al., C.A. (ed). 1965. Methods of soil analysis, part 2. Agronomy 9:771–1572. Am. Soc. of Agron., Madison, Wis.
7. Brockway, D.G. 1979. Evaluation of northern pine plantations as disposal sites for municipal and industrial sludge. Ph.D. Dissertation. Michigan State Univ., East Lansing. Univ. Microfilms, Ann Arbor, Mich. (Diss. Abstr. 40-2919B).
8. Brockway, D.G., and D.H. Urie. 1983. Determining sludge fertilization rates for forests based on nitrate-nitrogen in leachate and groundwater. J. Environ. Qual. (In Press).
9. Buckman, R.E. 1962. Growth and yield of red pine in Minnesota. USDA Forest Service, Lake States Forest Exp. Stn. Tech. Bull. no. 1272.
10. Chaney, R.L., S.B. Hornick, and P.W. Simon. 1977. Heavy metal relationships during land utilization of sewage sludge in the northeast. p. 261–281. *In* R.C. Loehr (ed.) Land as a waste management alternative. Ann Arbor Science Publishers, Ann Arbor, Mich.
11. Dahlquist, R.L., and J.W. Knoll. 1978. Inductively coupled plasma-atomic emission spectrometry: analysis of biological materials and soils for major, trace and ultra-trace elements. Appl. Spectros. 32:1–28.
12. Donov, U., T. Makedonska, and K. Yorova. 1977. Nutrient element accumulation and the production of certain assimilates in the needles (acerose leaves) of white pine seedlings following mineral fertilizer application. Fiziol Rast (Sofia) 3:69–77.
13. Fisher, R.F., and W.S. Garbett. 1980. Response of semimature slash and loblolly pine plantations to fertilization with nitrogen and phosphorus. Soil Sci. Soc. Am. J. 44:850–854.
14. Fitzgerald, P.R. 1982. Effects of natural exposure of cattle and swine to anaerobically digested sludge. p. 353–367. *In* W.E. Sopper et al. (ed.) Land reclamation and biomass production with municipal wastewater and sludge. The Pennsylvania State Univ. Press, University Park.
15. Forster, D.L., L.J. Logan, R.H. Miller, and R.K. White. 1977. State of the art in municipal sewage sludge landspreading. p. 603–618. *In* R.C. Loehr (ed.) Land as a waste management alternative. Ann Arbor Science Publishers, Ann Arbor, Mich.
16. Gerloff, G.C., D.G. Moore, and J.T. Curtis. 1964. Mineral content of native plants of Wisconsin. Univ. of Wisconsin Agric. Exp. Stn. Res. Report no. 14, Madison, Wis.
17. Harris, A.R. 1979. Physical and chemical changes in forested Michigan sand soils fertilized with effluent and sludge. p. 155–161. *In* W.E. Sopper and S.N. Kerr (ed.) Utilization of municipal sewage effluent and sludge on forest and disturbed land. The Pennsylvania State Univ. Press, University Park.
18. Heilman, P.E., and G.Ekuan. 1980. Phosphorus response of western hemlock seedlings on Pacific coast soils from Washington. Soil Sci. Soc. Am. J. 44:392–395.
19. Hippeli, P. 1976. Optimum level of nitrogen fertilization of pine stands poor in nutrients. Beitrage fur die Forstwirtschaft 10:112–116.
20. Kardos, L.T., C.E. Scarsbrook, and V.V. Volk. 1977. Recycling elements in wastes through soil-plant systems. p. 301–324. *In* L.F. Elliot and F.J. Stevenson (ed.) Soils for management of organic wastes and waste waters. Am. Soc. of Agron., Madison, Wis.
21. Leaf, A.L., R.E. Leonard, J.V. Berglund, A.R. Eschner, P.H. Cochran, J.B. Hart, G.M. Marion, and R.A. Cunningham. 1970. Growth and development of *Pinus resinosa* plantations subjected to irrigation-fertilization treatments. p. 97–118. *In* Tree growth and forest soils. Proc. of Third N. American Forest Soils Conf. August 1968, North Carolina State Univ., Raleigh. Oregon State Univ. Press, Corvallis.
22. Leaf, A.L., R.E. Leonard, R.F. Wittwer, and D.H. Bickelhaupt. 1975. Four year growth response of plantation red pine to potash fertilization and irrigation in New York. Forest Sci. 21:88–96.
23. Lindsay, W.L. 1973. Inorganic reactions of sewage wastes with soils. p. 91–96. *In* D.R. Wright et al. (ed.) Recycling sewage sludges and waste effluents on land. Nat. Assoc. State Univ. and Land-Grant Colleges, Washington, DC.
24. Lindsay, W.L., and W.A. Norwell. 1978. Development of a DTPA test for zinc, iron, manganese and copper. Soil Sci. Soc. Am. J. 42:421–428.
25. Mader, D.L., and J.A. Howarth. 1970. Relationships between foliar nutrient levels and tree growth in red pine stands in Massachusetts. p. 205–220. *In* Tree growth and forest soils. Proc. Third N. American Forest Soils Conf., August 1968. North Carolina State Univ., Raleigh. Oregon State Univ. Press, Corvallis.
26. McConnell, B.R., and J.G. Smith. 1970. Response of understory vegetation to ponderosa pine thinning in eastern Washington. J. Range Mgt. 23:208–212.
27. Milham, P.J., A.S. Awad, R.E. Paul, and J.H. Bull. 1970. Analysis of plants, soils and waters for nitrate by using an ion-selective electrode. Analyst. (London) 95:751–753.
28. Miller, H.G., and J.M. Cooper. 1973. Changes in amount and distribution of stem growth of pole-stage Corsica pine following application of nitrogen fertilizer. Forestry 46:157–190.
29. Miller, H.G., J.M. Cooper, and J.D. Miller. 1976. Effects of nitrogen supply on nutrients in litter fall and crown leaching in a stand of Corsican pine J. Appl. Ecol. 13:233–248.
30. Miller, H.G. 1981. Forest fertilization: some guiding concepts. Forestry 54:157–167.
31. Morrison, I.K., D.A. Winston, and N.W. Foster. 1976. Urea dosage trial in semimature jack pine forest, Chapleau, Ontario: fifth year results. Information Report no. 0-X-251. Great Lakes For. Res. Ctr., Canada.
32. Pritchett, W.L. 1977. The role of fertilizers in forest production. T.A.P.P.I. 60:14–77.
33. Pritchett, W.L. 1979. Properties and management of forest soils. John Wiley & Sons, Inc., New York.
34. Rawson, J.G. 1972. Response of thirty-to-forty-year-old retarded Radiata pine stands in Northland to aerial application of phospate. N.Z. J. For. 17:101–107.
35. Smith, W.H., and J.O. Evans. 1977. Special opportunities and problems in using forest soils for organic waste application. p. 429–454. *In* L.F. Elliott and F.J. Stevenson (ed.) Soils for management of organic wastes and waste waters. Am. Soc. of Agron., Madison, Wis.
36. Sommers, L.E. 1977. Chemical composition of sewage and analysis of their potential use as fertilizers. J. Environ. Qual. 6:225–232.
37. Street, J.J., W.L. Lindsay, and B.R. Sabey. 1977. Solubility and plant (corn) uptake of cadmium in soils amended with cadmium and sewage sludge. J. Environ. Qual. 6:72–77.
38. Tandon, H., M.P. Cescas, and E.H. Tyner. 1968. An acid-free vanadate-molybdate reagent for the determination of total phosphorus in soils. Soil Sci. Soc. Am. Proc. 32:48–51.
39. Technicon. 1971. Industrial method AAII 100-70W, p. 4901. *In* L.E. Harris (ed.) Nutrition research techniques for domestic and wild animals: Vol. 1. Utah State University, Logan.
40. Timmer, V.R., and E.L. Stone. 1978. Comparative foliar analysis of young balsam fir fertilized with nitrogen, phosphorus, potassium and lime. Soil Sci. Soc. Am. J. 42:125–130.
41. Timmer, V.R., E.L. Stone, and D.G. Embree. 1977. Growth response of young balsam fir fertilized with N, P, K and lime. Can. J. For. Res. 7:441–446.
42. Tolle, H. 1976. Increasing increment in old pine stands by nitrogen, fertilization in relation to stand density. Beitrage fur die Forstwirtschaft 10:117–120.
43. Turner, M.A. 1973. Effect of cadmium treatment on cadmium and zinc uptake by selected vegetable species. J. Environ. Qual. 2:118–119.
44. U.S. Environmental Protection Agency. 1974. Methods for chemical analysis of water and wastes. EPA Report no. EPA 625/6-74-003. U.S. Government Printing Office, Washington, DC.
45. Van Cleve, K., and T.A. Moore. 1978. Cumulative effects of nitrogen, phosphorus, and potassium fertilizer additions on soil respiration, pH and organic matter content. Soil Sci. Soc. Am. J. 42:121–124.
46. van den Driessche, R. 1974. Prediction of mineral nutrient status of trees by foliar analysis. Bot. Rev. 40:347–394.
47. White, D.P., and A.L. Leaf. 1956. Forest fertilization. College of Forestry Tech. Pub. no. 81, New York State Univ., Syracuse.
48. Wittwer, R.F., A.L. Leaf, and D.H. Bickelhaupt. 1975. Biomass and chemical composition of fertilized and/or irrigated *Pinus resinosa* Ait. plantations. Plant Soil 42:629–651.